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RESEARCH NOTE

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HIGH RANGE RESOLUTION RADAR CROSS-SECTION PROFILES - A PRELIMINARY ANALYSIS (U)

STEPHEN D. ELTON

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HIGH RANGE RESOLUTION RADAR CROSS-SECTION PROFILES - A PRELIMINARY ANALYSIS (U)

Stephen D. Elton

ABSTRACT (U)

We briefly review the technique of *stepped frequency imaging*, and describe the implementation of a computer program that calculates high range resolution radar cross-section profiles of maritime targets.

Postal Address: Director, Electronics Research Laboratory,
PO Box 1600, Salisbury, South Australia, 5108.

CONTENTS

LIST OF APPENDICES

LIST OF FIGURES

1 INTRODUCTION

The following provides a brief and informal account of an analysis technique used by the Electronic Warfare Division (EWD) to produce high range resolution radar cross-section (RCS) profiles of maritime targets. We begin by giving a simple theoretical discussion of the basic principle behind the technique employed, and then move on to describe the computer program used to carry out the first stage of the RCS analysis and make comparison with other work.

High range resolution RCS profiles, i.e. RCS as a function of range r, were derived for a maritime target with the use of a coherent radar system developed by the Microwave Radar Division (MRD). Synthetic range profiles were obtained for the ship by exploiting the reciprocal relationship that exists, in the context of the present work, between range and frequency (see Equation (3)), and by employing a fast Fourier transform (FFT) algorithm to evaluate the inverse discrete Fourier transform (IDFT). The technique is referred to in the literature as *stepped frequency imaging*, and involves the recording of radar returns from n pulses, such that the carrier frequency ν, for each successive pulse is incremented by a fixed amount $\Delta\nu$. The technique has been discussed by several authors, including Wehner et al. (1979), Prickett and Chen (1980), and Bryans (1986).

2 SOME THEORY

The purpose of this section is to "fill in some of the gaps" left by Wehner et al. (1979), and by Bryans (1986) in their theoretical discussion of stepped frequency imaging. The treatment presented by the latter author was actually based on other work, including that of Prickett and Chen (1980). According to Bryans (1986) provided the duration of the transmitted microwave pulse is large enough to enclose the entire target, the radar return $G(k)$ say, from an extended object at a range R, can be expressed as (refer to Figure 1) :-

$$G(k) = A \int F(r) \exp\left[-\frac{4\pi\imath}{c}(\nu_o + k\Delta\nu)(R - r)\right] dr, \tag{1}$$

where $F(r)$ is the target reflectivity function, A is a scale factor (a function of power and signal propagation for example), c denotes the speed of light, and $\imath = \sqrt{-1}$. The operating or carrier frequency ν_k, of the radar is given by :-

$$\nu_k = \nu_o + k\Delta\nu \qquad (k = 0, 1, \ldots, n-1). \tag{2}$$

Note that $F(r)$ is a continuous real function of range r, and $G(k)$ is a discrete complex function of the integer k (which in turn specifies the radar operating frequency). Furthermore, the limits of the integral not explicitly written in (1), are determined by the width of the transmitted radar pulse.

We can also write Equation (1) as :-

$$G(\nu) = A \int F(r) \exp(2\pi\imath\nu\Delta t) dr, \tag{3}$$

where $\Delta t = 2(r - R)/c$, and we have dropped the subscript notation on the frequency ν_k. That is, the argument of the exponential term in (1) and (3) represents the phase ϕ, of a returned signal relative to $\phi_o = 0$, defined at range $r = R$. Rearranging (1), we find that :-

$$H(k) = \int F(r) \exp\left[\frac{4\pi\imath}{c}(\nu_o + k\Delta\nu)r\right] dr, \tag{4}$$

where

$$H(k) = A^{-1} G(k) \exp\left[\frac{4\pi\imath}{c}(\nu_o + k\Delta\nu)R\right]. \tag{5}$$

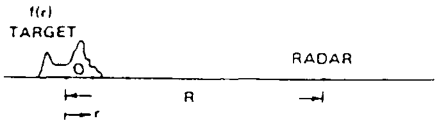

Figure 1 Target range geometry (after Prickett and Chen 1980).

We recognise Equation (4) as being a continuous Fourier transform that includes a phase shift term $\exp(4\pi\imath\nu_0 r/c)$. Hence, we can obtain the target reflectivity function F(r), from (4) via the following inverse continuous Fourier transform (ICFT) relationship :-

$$F(r) = \int H(k) \exp\left[-\frac{4\pi\imath}{c}(\nu_0 + k\Delta\nu)r\right] d\nu. \tag{6}$$

Whence the discrete version of (6) for n radar pulses is given by :-

$$F_l = \sum_{k=0}^{n-1} H_k \exp\left[-\frac{4\pi\imath}{c}(\nu_0 + k\Delta\nu)r_l\right] \qquad (l = 0, 1, \ldots, n-1). \tag{7}$$

In evaluating the magnitude of F_l (which we will ultimately be working with) the above phase shift term in Equation (7) is effectively removed. It is therefore more convenient to simply use :-

$$F_l = \sum_{k=0}^{n-1} H_k \exp(-2\pi\imath\lambda_k^{-1} r_l), \tag{8}$$

where $\lambda_k^{-1} = 2k\Delta\nu/c$. By analogy with a standard expression for the IDFT, for example :-

$$x_k = \frac{1}{n}\sum_{j=0}^{n-1} X_j \exp\left(-\frac{2\pi\imath jk}{n}\right) \qquad (k = 0, 1, \ldots, n-1), \tag{9}$$

we find that $r_l = cl/2n\Delta\nu$, and F_l can be evaluated using a FFT routine. The range resolution Δr, intrinsic to the above method via the FFT algorithm, is therefore :-

$$\Delta r = \frac{c}{2n\Delta\nu}, \tag{10}$$

which agrees with the formula given by Bryans (1986). In terms of the effective bandwidth $B = n\Delta\nu$, of the transmitted waveform, the range resolution can also be specified by the familiar expression :-

$$\Delta r = \frac{c}{2B}. \tag{11}$$

3 THE COMPUTER PROGRAM

At the time of writing, the most recent version of the computer program written to enable a preliminary analysis of the RCS data is called HIGH RES ANALYSIS 3 (refer to the program included as Appendix I). The input data files contain measurements of the in-phase (I) and quadrature (Q) components of $n = 256$ transmitted and received radar pulses per frame. The returned radar signal $C(k)$, can therefore be written as $G(k) = I_k + iQ_k$. Header information for each frame can also be extracted from the input files. An initial radar operating frequency ν_0 of 9.16 GHz was chosen, and a frequency increment of $\Delta\nu = 1$ MHz used for each of the 255 subsequent pulses. From Equation (10), the range resolution Δr, is then set at :-

$$\Delta r = \frac{3 \times 10^8}{2 \times 256 \times 10^6} \simeq 0.6 \text{ m}, \tag{12}$$

and yields an unambiguous range window $(n-1)\Delta r$, of approximately 150 m, which is large enough to enclose the selected target.

The FFT routine used in the program to evaluate Equation (8) via :-

$$F_l = \sum_{k=0}^{n-1} H_k \exp\left(-\frac{2\pi i k l}{n}\right) \qquad (l = 0, 1, \ldots, n-1), \tag{13}$$

was taken from p. 754 of *Numerical Recipes* (refer to Press et al. 1986). The storage convention of the input/output data array DATA1 is outlined in Appendix II. Once the data are windowed with the Hamming window function, and the n-point Fourier transform applied, the amplitude A, associated with the returned radar signal (a measure of the power returned from the target), is stored in an output file, together with the appropriate range value. The above amplitude of the radar return is presently defined as :-

$$A = |F_l| = \sqrt{F_l^* F_l}. \tag{14}$$

That is, the square root of the sum of the squares of the real and imaginary components of the IDFT. This can later be scaled in accordance with a standard calibration procedure to produce an estimate of RCS in the units of dBm^2 for example.

The result obtained from running the program on an input file is presented in Figure 2. The range profile was plotted using the graphics package CRICKET GRAPH. Good agreement is found with the corresponding plot for the same data provided by MRD (see Figure 3), although the latter result was obtained with an independent computer program developed by that Division.

Note that the output data files currently contain range and radar return values separated by a TAB, as required by CRICKET GRAPH. The computer program used in the next stage of the analysis, i.e. GRAPH MATCH, has been modified to allow for this. Refer to Bawden and Moon (1989) for further details concerning the use of GRAPH MATCH.

4 CONCLUSIONS

In this research note we have presented a simple theoretical discussion of a radar technique known as stepped frequency imaging. We have demonstrated the results that one can obtain with this technique, and shown these results to be in agreement with those produced by MRD for a particular data set.

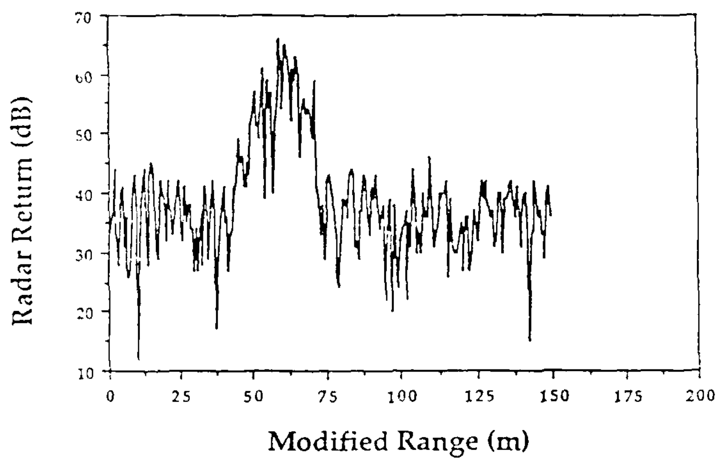

Figure 2 Example of range profile obtained with HIGH RES ANALYSIS 3 (see text)

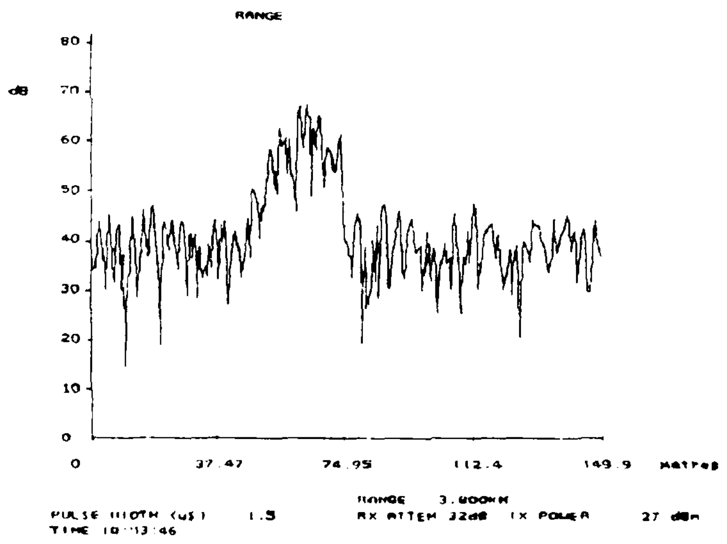

Figure 3 The corresponding range profile obtained by MRD for Figure 2.

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APPENDIX I

HIGH RES ANALYSIS 3

```
program high_res_analysis ;

{ *******************************************************************
  *                                                                 *
  * author    : P.W. Taliane and S.D. Elton                         *
  * date      : 13-Nov-1989                                         *
  * program   : calculates the RCS profile of a target using a high *
  *             resolution radar technique. The technique is based on the *
  *             ISAR method and employs a FFT routine in the analysis *
  *                                                                 *
  ******************************************************************* }

{$U+}    { autolink runtime units }
{$r+}

uses
  Memtypes ;
{,quickdraw,osintf,toolintf,
  PasInOut,PasConsole,SANE,PasPrinter,PackIntf,Turtle ;}

const
  header_start = 'TIME' ;
   n   = 256 ;
   PI  = 3.141593 ;
   nn2 = 512 ;               { used in }
   nn = 256 ;                { FFT     }
   isign = -1 ;              { routine }

type
 gldarray = array [1..nn2] of real ;
 Out_file  = array[1..2,1..256] of real ;
 in_file_data_type = Record
                       header  : Packed Array[1..256] of char ;
                       data    : array [1..256] of
                                   packed record
                                     TX_inphase,
                                     TX_quadrature,
                                     RX_inphase,
                                     RX_quadrature : byte ;
                                   end ;
                      end ;

var
 FR,FI,DatAmp : Out_file ;
 data1        : gldarray ;
 MAX_Power    : Array [1..2] of longint ;
 header       : str255 ;
 k,i          : integer ;
 input_file   : file of in_file_data_type ;
 file_data    : in_file_data_type ;
 word         : STRING;
 number       : real ;
 in_header    : boolean ;

{*********************** Assign Data ***********************}

procedure assign_data ;

{ assign recieved signal components to a data array that is to be Fourier
  transformed }

begin { assign_data }

  writeln('assign_data') ;
  for  i := 1 to n do
  begin
    data1[2*i-1] := fr[2,i]  ; data1[2*i] := -fi[2,i]  ;

 {       writeln('READ',char(9),data1[2*i-1],char(9),data1[2*i]) ;    }
  end;
```

```
end ; { assign_data }

{************************ HAMMING WINDOW ************************}

Procedure Hamming ;

{ window data using the Hamming window function }

Var
  a, i, k  : Integer ;
  windowi  : Real ;

Begin { Hamming }
 Writeln('Hamming') ;
 a := n ;
 For i := 1 to n do
  Begin
    windowi := 0.54-0.46 * cos(2.0 * pi * (i-1) /a) ;
    data1[2*i-1] := data1[2*i-1]*windowi ;
    data1[2*i] := data1[2*i]*windowi ;
  End ;

END ; { Hamming }

{************************ FAST FOURIER TRANSFORM ************************}

Procedure fft(var data1: gldarray; nn,isign: integer) ;

{ replaces DATA by its discrete Fourier transform, if ISIGN is input as 1; or
  replaces DATA by NN times its inverse dicrete Fourier transform, if ISIGN
  is input as -1. DATA is a complex array of length NN or, equivalently
  a real array of length 2*NN. NN must be an integer power of 2.

                         --- Numerical Recipes p. 754 }

var
 ii,jj,n,nn2,mmax,m,j,istep,i: integer ;
 wtemp,wr,wpr,wpi,wi,theta1: double ;   { double precision for the trignometric }
 tempr,tempi: real ;                    { recurrences }


begin
 writeln('FFT') ;
{ for i := 1 to 2*nn do
 begin
 writeln('FFT', data1[i]) ;
end ; }

 nn2 := 2*nn ;
 j := 1    ;
 for ii := 1 to nn do                 { this is the bit-reversal section of }
  begin                               { the routine }
  i := 2*ii-1 ;
  if (j>i) then begin
     tempr := data1[j] ;               { exchange the complex numbers }
     tempi := data1[j+1] ;
     data1[j] := data1[i] ;
     data1[j+1] := data1[i+1] ;
     data1[i] := tempr;
     data1[i+1] := tempi
  end ;
  m := nn2 div 2 ;
  while ((m >= 2) and (j > m)) do
    begin
      j := j-m ;
      m := m div 2
    end ;
    j := j+m
  end ;
  mmax := 2 ;                        { here begins the Danielson-Lanczos section of the r:
  while (nn2 > mmax) do                { outer loop executed log(2) NN times }
```

```
    begin
      istep := 2*mmax;
      theta1 := 6.28318530717959/(isign*mmax) ;     { initialise for trigonometric }
      wpr := -2.0*sqr(sin(0.5*theta1)) ;             { recurrence }
      wpi := sin(theta1);
      wr := 1.0 ;
      wi := 0.0 ;
      for ii := 1 to (mmax div 2) do                 { here are the two nested loops }
        begin
          m := 2*ii-1 ;
          for jj := 0 to ((nn2-m) div istep) do
          begin
            i := m + jj*istep;
            j := i+mmax;                              { this is the Danielson formula }
            tempr := wr*data1[j]-wi*data1[j+1];
            tempi := wr*data1[j+1]+wi*data1[j];
            data1[j] := data1[i]-tempr;
            data1[j+1] := data1[i+1]-tempi ;
            data1[i] := data1[i]+tempr;
            data1[i+1] := data1[i+1]+tempi
          end ;
          wtemp := wr;                                { trigonometric recurrence }
          wr := wr*wpr-wi*wpi+wr ;
          wi := wi*wpr+wtemp*wpi+wi
        end ;
        mmax := istep
    end
end ; {FFT}

{************************* Read Data In *************************}

Procedure Read_Data_In( var k : integer ) ;

var
 TX_inphase,
 TX_quadrature,
 RX_inphase,
 RX_quadrature : integer ;

 { read data from i/p file. data corresponds to the transmitted and
   received signals and is stored in terms of the in phase and quadrature
   components }

begin { read data in }
 writeln('Read') ;
 writeln('****************************************') ;
 writeln ;
 read(input_file,file_data) ;
 moveleft(file_data.header,header[1],255) ;        { extract title from header }
 header[0] := chr(255) ;
 writeln(header) ;

 for i := 1 to n  do
 begin
  TX_inphase    := file_data.data[i].TX_inphase - 128 ;
  TX_quadrature := file_data.data[i].TX_quadrature - 128 ;
  RX_inphase    := file_data.data[i].RX_inphase - 128 ;
  RX_quadrature := file_data.data[i].RX_quadrature - 128 ;

  fr[1,i] := TX_inphase ;     {FR & FI 1 Transmit}
  fi[1,i] := TX_quadrature ;
  fr[2,i] := RX_inphase ;     {FR & FI 2 Receive}
  fi[2,i] := RX_quadrature ;

 {  Writeln(' READ ',i-1,char(9),fr[1,i]:4,fi[1,i]:4,fr[2,i]:4,fi[2,i]:4) ; }

 end ;
 writeln('****************************************') ;
end ; { read data in }

{************************* Read Data Out *************************}
```

```
Procedure Write_data_out ;

const
  c = 3.0e8 ;
  freqinc = 1.0e6 ;

var
  i, j          : Integer ;
  spec          : out_file ;
  file_name     : Str255 ;
  output_file   : text ;
  index         : integer ;
  range         : real ;
  amp, amp1     : real ;
  amp2          : byte ;

begin { write data out }
  writeln('Write') ;
  file_name := concat(copy(header,142,7),' run ',copy(header,48,4)) ;
  rewrite(output_file,file_name) ;
  writeln(output_file,header) ;
  writeln(output_file,'****************************************') ;
  writeln(output_file) ;
  writeln(output_file) ;


      index := 0 ;
      for j := -n div 2 to n div 2 - 1 do
       begin
         range := (c*index)/(2.0*freqinc*n) ;    { convert index associated with
         index := index + 1 ;                      { FFT to modified range }
         if j < 0 then i := j + n
         else i := j ;
         i := i+1 ;
         amp := data1[2*i-1]*data1[2*i-1]+data1[2*i]*data1[2*i] ;
         amp1 := 10.0 * ln (amp) * 0.4343 ;                  { log(x) = ln(x)*0.4343) }
         amp2 := round(amp1) ;

     {   writeln(output_file,range:4:1,char(9),amp2:8) ; }
        writeln(output_file,range:5:2,char(9),amp1:5:2) ;
      end ;

    {      writeln(output_file,(20*ln(DatAmp[1,i])*0.4343):6,Chr(9),
                               (20*ln(DatAmp[2,i])*0.4343):6,Chr(9)
                               ) ;}

      close(output_file) ;
 end ; { write data out }

{************************* Main Progam ************************}

 begin
   reset(input_file,'rcs100.dat') ;
   for k := 1 to 2 do
     begin
       Read_Data_In( k ) ;
       assign_data ;
       Hamming ;
       FFT(data1,nn,isign) ;
       Write_data_out ;
     end ;
     readln ;
end.
```

APPENDIX II

FFT STORAGE CONVENTION

Figure II.1 illustrates the storage convention for the input/output data array DATA1 contained in the program HIGH RES ANALYSIS 3. The input array (refer to (a)) contains N (a power of 2) complex data samples in a real array of length $2N$, with real and imaginary components alternating. The output array (refer to (b)) contains the complex Fourier spectrum. Again the real and imaginary components alternate. The array begins with zero frequency, and builds up to the most positive frequency. Negative frequencies then follow, starting with the second most negative frequency (remember the most positive and negative frequencies are ambiguous), up to the frequency just below zero.

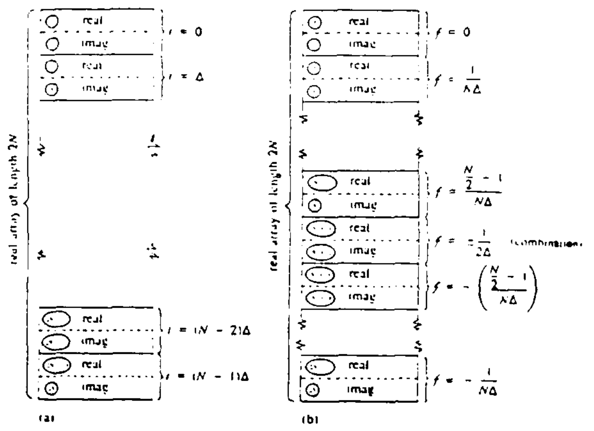

Figure II.1 Storage convention for input/output data array DATA1 (after Press et al. 1986).

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